

(12) **United States Patent**  
**Tan et al.**

(10) **Patent No.:** **US 9,423,000 B2**  
(45) **Date of Patent:** **\*Aug. 23, 2016**

(54) **MAGNETICALLY SUSPENDED VIBRATION ISOLATOR WITH ZERO STIFFNESS WHOSE ANGLE DEGREE OF FREEDOM IS DECOUPLED WITH A JOINT BALL BEARING**

5/20 (2013.01); *G01L 19/0061* (2013.01);  
*H02K 41/0356* (2013.01)

(58) **Field of Classification Search**

CPC ... F16F 15/03; F16F 15/002; F16C 32/0614;  
G01B 7/003; G01D 5/20; G01L 19/00;  
H02K 41/0356; G03F 7/70833  
USPC ..... 248/550, 638, 644, 678  
See application file for complete search history.

(71) Applicant: **HARBIN INSTITUTE OF TECHNOLOGY**, Harbin, Heilongjiang (CN)

(72) Inventors: **Jiubin Tan**, Heilongjiang (CN);  
**Junning Cui**, Heilongjiang (CN); **Lei Wang**, Heilongjiang (CN)

(73) Assignee: **Harbin Institute of Technology**, Harbin (CN)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,548,170 A \* 8/1996 Shultz ..... F16C 32/0651  
310/90.5  
5,573,088 A \* 11/1996 Daniels ..... B60G 17/0157  
188/267

(Continued)

FOREIGN PATENT DOCUMENTS

CN 102537196 A 7/2012  
CN 102734379 A 10/2012

(Continued)

OTHER PUBLICATIONS

Espacenet English abstract of EP 1 803 970 A2.

(Continued)

Primary Examiner — Gwendolyn Baxter

(74) Attorney, Agent, or Firm — Ladas & Parry LLP

(57) **ABSTRACT**

A magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing has a main body, in which a sleeve and a lower mounting plate are supported with a magnetically suspended thrust bearing, a piston cylinder and the sleeve are lubricated and supported with a cylinder air bearing surface, and the angle degree of freedom between an upper mounting plate and the lower mounting plate is decoupled with a joint ball bearing; a position close-loop control system comprising voice coil motors, displacement sensors, limit switches, a controller and a driver is introduced, and the relative position between the upper mounting plate and the lower mounting plate is precisely controlled.

**4 Claims, 3 Drawing Sheets**

(21) Appl. No.: **14/421,610**

(22) PCT Filed: **Feb. 19, 2014**

(86) PCT No.: **PCT/CN2014/072279**

§ 371 (c)(1),

(2) Date: **Feb. 13, 2015**

(87) PCT Pub. No.: **WO2014/094689**

PCT Pub. Date: **Jun. 26, 2014**

(65) **Prior Publication Data**

US 2015/0260255 A1 Sep. 17, 2015

(30) **Foreign Application Priority Data**

Dec. 19, 2012 (CN) ..... 2012 1 0574709

(51) **Int. Cl.**

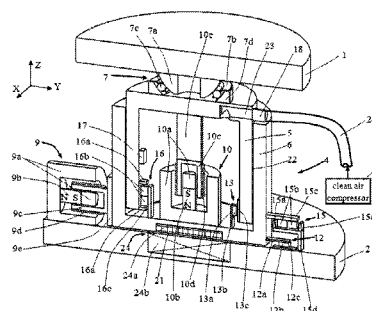
**F16M 13/00** (2006.01)

**F16F 15/03** (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ..... *F16F 15/03* (2013.01); *F16F 15/002* (2013.01); *F16F 15/0232* (2013.01); *G01D*



(51)	<b>Int. Cl.</b>		CN	103047361	A	4/2013
	<b>F16F 15/023</b>	(2006.01)	CN	103062299	A	4/2013
	<b>F16F 15/00</b>	(2006.01)	CN	103062300	A	4/2013
	<b>G01D 5/20</b>	(2006.01)	CN	103062303	A	4/2013
	<b>G01L 19/00</b>	(2006.01)	EP	1 486 825	A1	12/2004
	<b>H02K 41/035</b>	(2006.01)	EP	1 803 970	A2	7/2007
			EP	1803965	A2	7/2007
			JP	2004100953	A	4/2004
			JP	2005-331009	A	12/2005
			JP	2012-156304	A	8/2012
			WO	99/22272	A1	5/1999

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,844,664	A	12/1998	Van Kimmenade et al.
6,144,442	A	11/2000	T Mannetje et al.
7,084,956	B2	8/2006	Dams et al.
2004/0065517	A1	4/2004	Watson et al.
2008/0193061	A1	8/2008	Heiland
2010/0284638	A1 *	11/2010	Hirata ..... F16C 32/067 384/100
2014/0374565	A1 *	12/2014	Tan ..... F16F 15/023 248/542
2015/0219179	A1 *	8/2015	Cui ..... F16F 15/03 248/550
2015/0219180	A1 *	8/2015	Tan ..... F16F 15/03 248/550

FOREIGN PATENT DOCUMENTS

CN	103032515	A	4/2013
CN	103047346	A	4/2013

OTHER PUBLICATIONS

English Abstract of CN 103047346 A.  
English Abstract of CN 103062299 A.  
English Abstract of CN 103062300 A.  
English Abstract of CN 103062303 A.  
English Abstract of CN 103047361 A.  
English Abstract of CN 103032515 A.  
English Abstract of CN 102734379 A.  
English Abstract of CN 102537196 A.  
English Abstract of JP 2012-156304 A.  
English Abstract of JP 2005-331009A.  
English Abstract of EP 1803965A2.  
English Abstract of JP 2004100953A.

\* cited by examiner

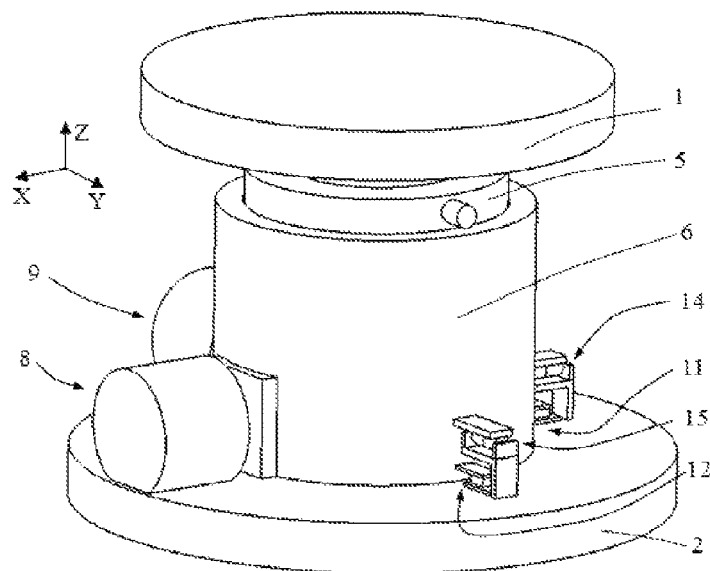


Fig. 1

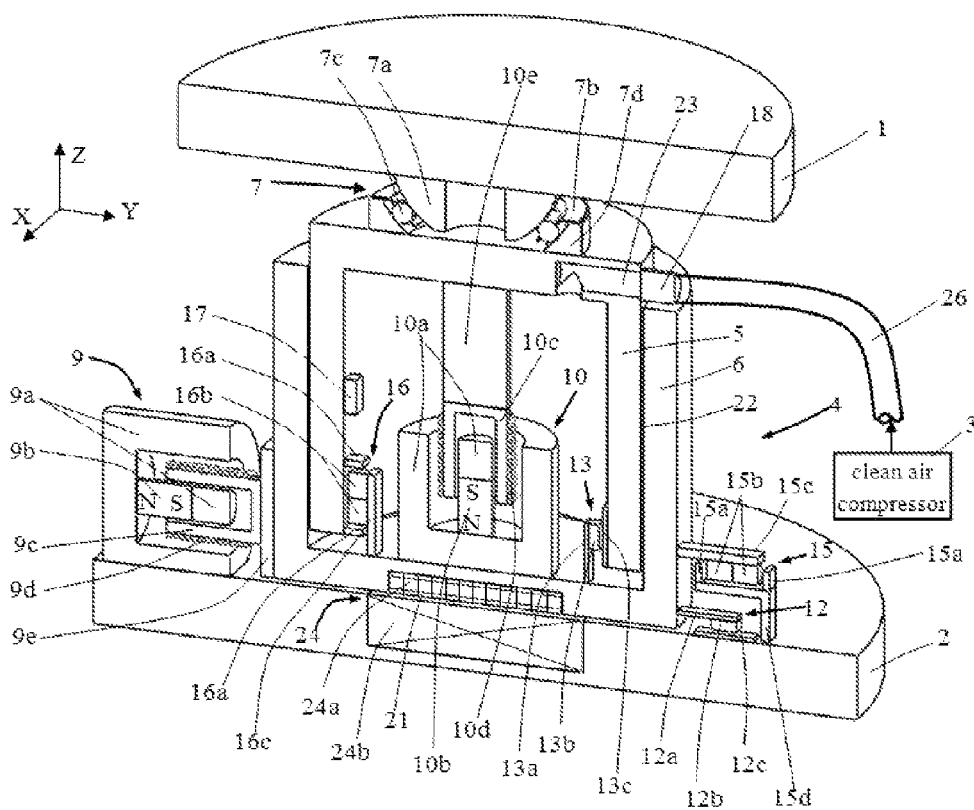


Fig. 2

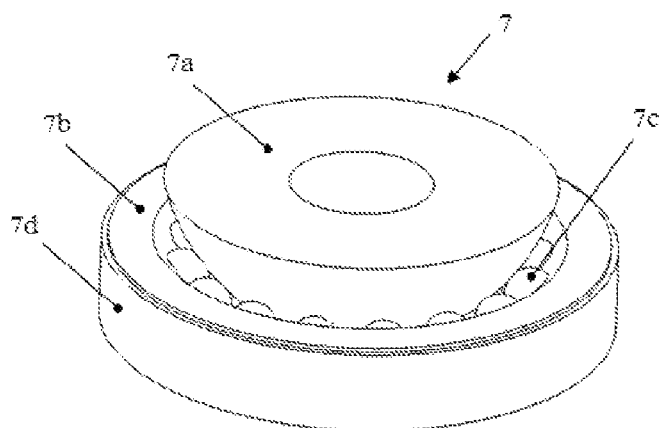


Fig. 3

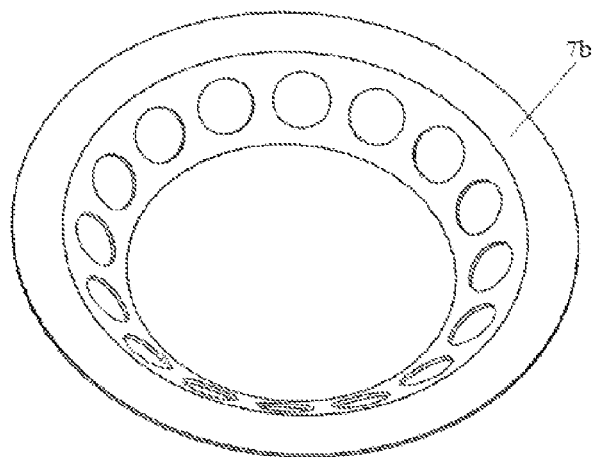


Fig. 4

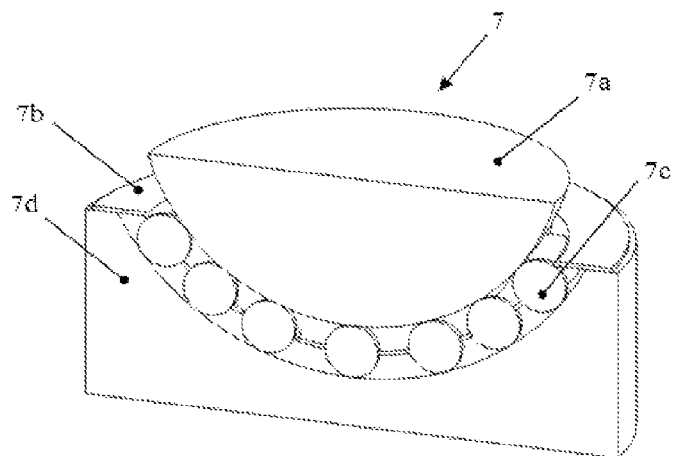


Fig. 5

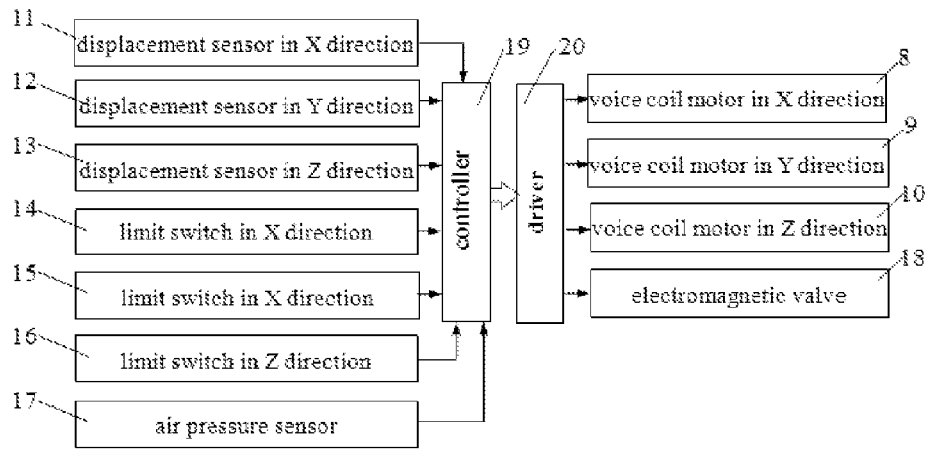


Fig. 6

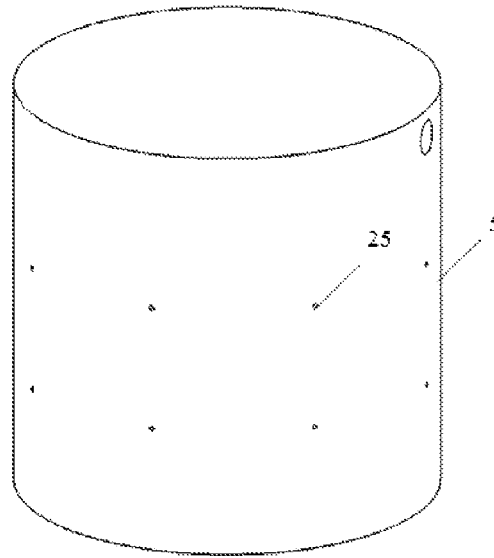


Fig. 7

1

**MAGNETICALLY SUSPENDED VIBRATION  
ISOLATOR WITH ZERO STIFFNESS WHOSE  
ANGLE DEGREE OF FREEDOM IS  
DECOUPLED WITH A JOINT BALL  
BEARING**

CROSS-REFERENCE TO RELATED  
APPLICATION

This U.S. application claims priority under 35 U.S.C. 371 to, and is a U.S. National Phase application of, the International Patent Application No. PCT/CN2014/072279, filed 19 Feb. 2014, which claims the benefit of prior Chinese Application No. 201210574709.3 filed 19 Dec. 2012. The entire contents of the above-mentioned patent applications are incorporated by reference as part of the disclosure of this U.S. application.

FIELD OF INVENTION

The present invention relates to a magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing, which can be used for low frequency and high performance vibration isolation in precision measurement instruments and manufacturing equipments.

DESCRIPTION OF PRIOR ART

With quick development of precision measurement and manufacturing, environmental vibration has become a main factor that limits the precision and performance of precision measuring instruments and manufacturing equipments. For example, step-scan lithography machines are most precise among all kinds of manufacturing equipments, their line width of lithography is up to 22 nm, and their wafer positioning precision and overlay precision is up to several nanometers. Meanwhile, movement speed of their wafer stages is up to 1 ms, and acceleration is up to dozens of times of gravitational acceleration. For such ultra-precision equipments, precision vibration isolation is a key technology. On one hand, a very quiet environment should be provided for measuring systems and objective lens, while wafer stages should be moved with high speed and acceleration. 3D nature frequencies of the vibration isolation system should be smaller than 1 Hz. On the other hand, relative position between key parts in a lithography machine, such as the distance between objective lens and wafers, should be precisely controlled, control precision of the relative position between upper mounting plates and lower mounting plates of vibration isolators should reach 10  $\mu\text{m}$ .

The natural frequency of a passive vibration isolator is proportional to its stiffness, and inversely proportional to its mass. Therefore it is a very efficient way to lower the natural frequency of a vibration isolator and improve its performance through reducing its stiffness. However, for a traditional vibration isolator based on an air spring, it's very difficult to further reduce its stiffness, especially horizontal stiffness. To solve this problem, researchers introduce a "pendulum" structure in vibration isolators based on air springs to reduce the horizontal stiffness (1. Nikon Corporation. Vibration Isolator with Low Lateral Stiffness. U.S. Patent No. US20040065517A1; 2. U.S. Philips Corporation. Positioning Device with a Force Actuator System for Compensating Center-of-gravity Displacements, and Lithographic Device Provided with Such A Positioning Device.

2

U.S. Patent No. 5,844,664A). With this method, lateral stiffness of a vibration isolator based on an air spring can be reduced and its performance can be improved to a certain extent. However, there are still following shortcomings: 1) the extent of reduction of horizontal and vertical stiffness is limited by material property and structural stiffness; 2) horizontal and vertical positioning precision of a vibration isolator based on an air spring is too low to meet the requirement of lithography; 3) a large length of "pendulum" is needed to achieve low horizontal stiffness, easily results large height of vibration isolators, chord-membrane-resonance and poor stability.

It's difficult to meet requirements of low stiffness and high positioning precision in a lithography machine with existing vibration isolators based on air springs. German company IDE presents a new vibration isolator design (1. Integrated Dynamics Engineering GmbH. Isolatorgeometrie Eines Schwingungsisolationsystem. European Patent No.: EP1803965A2; 2. Integrated Dynamics Engineering GmbH. Schwingungsisolationsystem Mit Pneumatischem Tiefpassfilter. European Patent No.: EP1803970A2; 3. Integrated Dynamics Engineering GmbH. Air Bearing with Consideration of High-Frequency Resonances. U.S. Patent No. US20080193061A1). Air bearing surfaces are introduced to decouple and isolate vertical and horizontal vibration, and very low stiffness and natural frequency can be achieved. However, there are still following shortcomings: 1) high positioning precision can't be achieved with presented design; 2) in patent EP1803965A2, there is no rotary degree of freedom around horizontal axes between the upper and lower mounting plates, so stiffness and natural frequency in that direction are both high; in patents EP1803970A2 and US20080193061A1, a rubber block is used to provide the rotary degree of freedom around horizontal axes, however, the angle degree of freedom can't be effectively decoupled due to large angular stiffness of the rubber block.

Netherlandish company ASML has proposed a similar design (1. U.S. Philips Corp, ASM Lithography B.V. Pneumatic Support Device with A Controlled Gas Supply, and Lithographic Device Provided with Such A Support Device. U.S. Pat. No. 6,144,442A; 2. Koninklijke Philips Electronics N. V., ASM Lithography B. V. Lithographic Pneumatic Support Device with Controlled Gas Supply. International patent publication No.: WO9922272; 3. ASML Netherlands B. V. Support Device, Lithographic Apparatus, and Device Manufacturing Method Employing A Supporting Device, and A Position Control System Arranged for Use in A Supporting Device. U.S. Pat. No. 7,084,956B2; 4. ASML Netherlands B.V. Support Device, Lithographic Apparatus, and Device Manufacturing Method Employing A Supporting Device and A Position Control System Arranged for Use in A Supporting Device. European Patent No.: EP1486825A1). The air pressure is close-loop controlled to increase stability and performance of vibration isolators in U.S. Pat. No. 6,144,442A and WO9922272. A vibration sensor is mounted on the upper mounting plate and a reference system is introduced as well to improve performance of vibration isolation in U.S. Pat. No. 7,084,956B2 and EP1486825A1. However, problems of precision positioning and decoupling of angle degree of freedom between the upper and lower mounting plates are still not solved.

SUMMARY OF INVENTION

In order to solve the problem of precision positioning and decoupling of angle degree of freedom between the upper

and lower mounting plates, the present invention provides a vibration isolator with 3D zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing, and it can be used for high performance vibration isolation in precision measuring instruments and manufacturing equipments, such as step-scan lithography machines.

The present invention provides a magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing, which comprises an upper mounting plate, a lower mounting plate, a clean air compressor, an air pipe and a main body, the main body is fitted between the upper mounting plate and the lower mounting plate, and the clean air compressor is connected to the main body via the air pipe; in the main body, the lower surface of a downside-down sleeve and the lower mounting plate are lubricated and supported against each other with a magnetically suspended thrust bearing, an upside-down piston cylinder is fitted inside the sleeve and they are lubricated against each other with a cylindrical air bearing surface, a joint ball bearing is fitted between the piston cylinder and the upper mounting plate, a voice coil motor in Z direction, a displacement sensor in Z direction and a limit switch in Z direction are fitted between the piston cylinder and the sleeve, a voice coil motor in X direction, a displacement sensor in X direction and a limit switch in X direction as well as a voice coil motor in Y direction, a displacement sensor in Y direction and a limit switch in Y direction are fitted between the sleeve and the lower mounting plate, the direction of driving force of the voice coil motor in Z direction is vertical, while the direction of driving force of the voice coil motor in X direction and the voice coil motor in Y direction is horizontal and perpendicular to each other, the sensitive direction of the displacement sensor in X direction, the displacement sensor in Y direction and the displacement sensor in Z direction as well as the limit switch in X direction, the limit switch in Y direction and the limit switch in Z direction are the same as the direction of driving force of the voice coil motor in X direction, the voice coil motor in Y direction and the voice coil motor in Z direction respectively; the displacement sensor in X direction, the displacement sensor in Y direction and the displacement sensor in Z direction as well as the limit switch in X direction, the limit switch in Y direction and the limit switch in Z direction are connected to signal input terminals of a controller, signal output terminals of the controller are connected to signal input terminals of a driver, and signal output terminals of the driver are connected to the voice coil motor in X direction, the voice coil motor in Y direction and the voice coil motor in Z direction respectively.

Preferably an air pressure sensor is fitted inside the piston cylinder, there is an air inlet and an electromagnetic valve in the piston cylinder, the air pressure sensor is connected to a signal input terminal of the controller, a signal output terminal of the controller is connected to a signal input terminal of the driver, a signal output terminal of the driver is connected to the electromagnetic valve.

Preferably the magnetically suspended thrust bearing is configured as follows: a magnet block of bearing is fitted on the bottom of the sleeve, a coil of bearing is oppositely fitted on the top of the lower mounting plate, and the thickness of the gap of magnetic suspending is 0.01 mm~1 mm.

The voice coil motor in X direction, the voice coil motor in Y direction and the voice coil motor in Z direction are cylindrical voice coil motors or flat voice coil motors.

The displacement sensor in X direction, displacement sensor in Y direction and displacement sensor in Z direction are grating rulers, magnetic grid rulers, capacitive grid rulers or linear potentiometers.

The limit switch in X direction, limit switch in Y direction and limit switch in Z direction are mechanical limit switches, Hall limit switches or photoelectric limit switches.

Preferably the air pressure inside said piston cylinder is 0.1 MPa~0.8 MPa.

The present invention has following advantages:

(1) Neglectable friction, wear and additional stiffness introduced into vibration isolators during decoupling of angle degree of freedom. In the present invention a joint ball bearing is used to decouple the angle degree of freedom between the upper and lower mounting plates, and the problem of friction, wear and introduction of additional stiffness of existing designs and patents during decoupling with elastic body can be successfully solved.

(2) Approximate 3D zero stiffness so that outstanding low frequency vibration isolation performance can be achieved. In the present invention, a magnet suspended thrust bearing and a cylindrical air bearing surface are employed to decouple and isolation vibration in horizontal and vertical directions, the difficulty of achieving very low stiffness and contradiction between stiffness and stability of existing designs and patents can be solved.

(3) High positioning precision for relative position control between the upper and lower mounting plates. The present invention employs voice coil motors, displacement sensors, limit switches, a controller and a driver to form position close-loop control systems in vertical and horizontal directions, so that the relative position between the upper and lower mounting plates can be precisely controlled with precision up to 10  $\mu$ m. The problem of low positioning precision and contradiction between positioning precision and stiffness of existing design and patents can be solved.

(4) Ideal gravity balance for excellent vertical vibration isolation with zero stiffness. The present invention employs an air pressure sensor, an electromagnetic valve, a controller and a driver to form an air pressure close-loop control system, so that the air pressure inside the sleeve is precisely controlled, and the gravity of vertical load of the vibration isolator can be balanced very precisely.

#### BRIEF DESCRIPTION OF ACCOMPANYING DRAWINGS

FIG. 1 is a structural diagram of the magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing.

FIG. 2 is a 3D cross-sectional view of the magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing.

FIG. 3 is a structural diagram of a joint ball bearing with a single row of balls.

FIG. 4 is a structural diagram of the ball holder of a joint ball bearing with a single row of balls.

FIG. 5 is a structural diagram of a joint ball bearing with fully distributed balls.

FIG. 6 is a control block diagram of the magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing.

FIG. 7 is one embodiment of throttle holes in the cylindrical air bearing surface of the piston cylinder.

## DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will be described in detail with reference to accompanying drawings.

As shown in FIG. 1, FIG. 2 and FIG. 3, a magnetically suspended vibration isolator with zero stiffness whose angle degree of freedom is decoupled with a joint ball bearing comprises a upper mounting plate 1, a lower mounting plate 2, a clean air compressor 3, an air pipe 26 and a main body 4, the main body 4 is fitted between the upper mounting plate 1 and the lower mounting plate 2, and the clean air compressor 3 is connected to the main body 4 with the air pipe 26; in the main body 4, the lower surface of a downside-down sleeve 6 and the lower mounting plate 2 are lubricated and supported against each other with a magnetically suspended thrust bearing 24, a upside-down piston cylinder 5 is fitted inside the sleeve 6 and they are lubricated against each other with a cylindrical air bearing surface 22, a joint ball bearing 7 is fitted between the piston cylinder 5 and the upper mounting plate 1, a voice coil motor in Z direction 10, a displacement sensor in Z direction 13 and a limit switch in Z direction 16 are fitted between the piston cylinder 5 and the sleeve 6, a voice coil motor in X direction 8, a displacement sensor in X direction 11 and a limit switch in X direction 14 as well as a voice coil motor in Y direction 9, a displacement sensor in Y direction 12 and a limit switch in Y direction 15 are fitted between the sleeve 6 and the lower mounting plate 2, the direction of driving force of the voice coil motor in Z direction 10 is vertical, while the direction of driving force of the voice coil motor in X direction 8 and voice coil motor in Y direction 9 is horizontal and perpendicular to each other, the sensitive direction of the displacement sensor in X direction 11, the displacement sensor in Y direction 12 and the displacement sensor in Z direction 13 as well as the limit switch in X direction 14, the limit switch in Y direction 15 and the limit switch in Z direction 16 are the same as the direction of driving force of the voice coil motor in X direction 8, the voice coil motor in Y direction 9 and the voice coil motor in Z direction 10 respectively; the displacement sensor in X direction 11, the displacement sensor in Y direction 12 and the displacement sensor in Z direction 13 as well as the limit switch in X direction 14, the limit switch in Y direction 15 and the limit switch in Z direction 16 are connected to signal input terminals of a controller 19, signal output terminals of the controller 19 are connected to signal input terminals of a driver 20, and signal output terminals of the driver 20 are connected to the voice coil motor in X direction 8, the voice coil motor in Y direction 9 and the voice coil motor in Z direction 10 respectively.

Preferably an air pressure sensor 17 is fitted inside the piston cylinder 5, there is an air inlet 23 and an electromagnetic valve 18 in the piston cylinder 5, the air pressure sensor 17 is connected to a signal input terminal of the controller 19, a signal output terminal of the controller 19 is connected to a signal input terminal of the driver 20, a signal output terminal of the driver 20 is connected to the electromagnetic valve 18.

Preferably the magnetically suspended thrust bearing 24 is configured as follows: a magnet block of bearing 24a is fitted on the bottom of the sleeve 6, a coil of bearing 24b is oppositely fitted on the top of the lower mounting plate 2, and the thickness of the gap of magnetic suspending 21 is 0.01 mm~1 mm.

The voice coil motor in X direction 8, the voice coil motor in Y direction 9 and the voice coil motor in Z direction 10 are cylindrical voice coil motors or flat voice coil motors.

The displacement sensor in X direction 11, displacement sensor in Y direction 12 and displacement sensor in Z direction 13 are grating rulers, magnetic grid rulers, capacitive grid rulers or linear potentiometers.

The limit switch in X direction 14, limit switch in Y direction 15 and limit switch in Z direction 16 are mechanical limit switches, Hall limit switches or photoelectric limit switches.

Preferably the air pressure inside said piston cylinder 5 is 0.1 MPa~0.8 MPa.

One embodiment of the prevent invention is provided with reference to FIG. 1, FIG. 2 and FIG. 6. In this embodiment, the lower mounting plate 2 is fitted onto the base of measurement instruments or manufacturing equipments, and the upper mounting plate 1 is fitted onto the load to be vibration isolated. The voice coil motor in X direction 8, the voice coil motor in Y direction 9 and the voice coil motor in Z direction 10 are cylindrical voice coil motors. Take the voice coil motor in Y direction 9 for example, it comprises an iron yoke of motor Y 9a, a magnetic block of motor Y 9b, a coil skeleton of motor Y 9c, a coil of motor Y 9d and a mounting piece of motor Y 9e. The iron yoke of motor Y 9a, the magnetic block of motor Y 9b, and the coil skeleton of motor Y 9c are cylindrical, the coil of motor Y 9d is wound around the coil skeleton of motor Y 9c, the mounting piece of motor Y 9e provide a mounting structure for the coil skeleton of motor Y 9c. According to electromagnetic theory, magnitude and direction of driving force which the motor outputs can be precisely controlled by adjusting magnitude and direction of current in the coil.

In this embodiment, the displacement sensor in X direction 11, the displacement sensor in Y direction 12 and the displacement sensor in Z direction 13 are grating rulers. Take the displacement sensor in Z direction 13 for example, it comprises a mounting piece of grating Z 13a, a reading head of grating Z 13b and a glass ruler of grating Z 13c. The mounting piece of grating Z 13a provides a mounting structure for the reading head of grating Z 13b. The reading head of grating Z 13b can detect the relative displacement between itself and the glass ruler of grating Z 13c, and then deliver the displacement signal to the controller 19.

In this embodiment, the limit switch in X direction 14, the limit switch in Y direction 15 and the limit switch in Z direction 16 are Hall limit switches. Take the limit switch in Z direction 16 for example, it comprises two limit blocks of switch Z 16a, two Hall switches of switch Z 16b and a mounting piece of switch Z 16c. Two Hall switches of switch Z 16b are fitted back to back against each other. The mounting piece of switch Z 16c provides a mounting structure for two Hall switches of switch Z 16b. When two Hall switches of switch Z 16b are moved close to limit blocks of switch Z 16a, a limit signal will be generated and delivered to the controller 19.

In this embodiment, the voice coil motor in Z direction 10, the displacement sensor in Z direction 13 and the limit switch in Z direction 16 are all fitted between the piston cylinder 5 and the sleeve 6 and inside the piston cylinder 5.

The load of the presented vibration isolator is supported in such a way: the clean air compressor 3 feeds clean compressed air into the piston cylinder 5 via the air pipe 26, the electromagnetic valve 18 and the air inlet 23. The controller 19 adjusts the open degree of the electromagnetic valve 18 according the feedback signal of the air pressure sensor 17. As a result, the air pressure in the piston cylinder



7

5 is precisely adjusted so that the upward force applied on the piston cylinder 5 is balanced with load, gravity of the piston cylinder 5 and other parts fitted together with it.

In this embodiment, the pressure of clean compressed air in the piston cylinder 5 is 0.4 Mpa, the effective radius of the lower surface of the piston cylinder 5 is 100 mm, so the mass that a single vibration isolator can support is:  $m = p \times \pi r^2 / g = 1282$  kg, where  $p$  is the air pressure,  $p = 0.4$  Mpa,  $r$  is the effective radius of the lower surface of the piston cylinder 5,  $r = 100$  mm, and  $g$  is the gravity acceleration,  $g = 9.8$  mm<sup>2</sup>.

A preferred embodiment of a joint ball bearing with a single row of balls is provided with reference to FIG. 3 and FIG. 4. In this embodiment, the joint ball bearing 7 mainly comprises the bearing body 7a, the ball holder 7b, the ball 7c and the bearing base 7d. The ball 7c is distributed in a circle row around the center. There are holes in the ball holder 7b at the corresponding position of the ball 7c, and the balls 7c are held in place by the ball holder 7b.

A preferred embodiment of a joint ball bearing with fully distributed balls is provided with reference to FIG. 5. In this embodiment, the ball 7c are fully distributed between the bearing body 7a and the bearing base 7d. The ball holder 7b is spherical, and there are holes in the ball holder 7b at the corresponding position of the ball 7c, and the balls 7c are held in place by the ball holder 7b.

A preferred embodiment of throttle holes in cylindrical air bearing surface of sleeve 6 is provided with reference to FIG. 7. In this embodiment, two rows of throttle holes in cylindrical air bearing surface 25 are uniformly distributed in a circle direction in the side wall of the piston cylinder 5. There are 8 throttle holes with diameter of  $\phi 0.2$  mm in each row.

In the accompanying drawings:

upper mounting plate 1  
lower mounting plate 2  
clean air compressor 3  
main body 4  
piston cylinder 5  
sleeve 6  
joint ball bearing 7  
bearing body 7a  
ball holder 7b  
ball 7c  
bearing base 7d  
voice coil motor in X direction 8  
voice coil motor in Y direction 9  
iron yoke of motor Y 9a  
magnetic block of motor Y 9b  
coil skeleton of motor Y 9c  
coil of motor Y 9d  
mounting piece of motor Y 9e  
voice coil motor in Z direction 10  
iron yoke of motor Z 10a  
magnetic block of motor Z 10b  
coil skeleton of motor Z 10c  
coil of motor Z 10d  
mounting piece of motor Z 10e  
displacement sensor in X direction 11  
displacement sensor in Y direction 12  
mounting piece of grating Y 12a  
reading head of grating Y 12b  
glass ruler of grating Y 12c  
displacement sensor in Z direction 13  
mounting piece of grating Z 13a  
reading head of grating Z 13b  
glass ruler of grating Z 13c  
limit switch in X direction 14

8

limit switch in Y direction 15  
limit block of switch Y 15a  
Hall switch of switch Y 15b  
mounting piece of switch Y 15c  
mounting piece of limit Y 15d  
limit switch in Z direction 16  
limit block of switch Z 16a  
Hall switch of switch Z 16b  
mounting piece of switch Z 16c  
air pressure sensor 17  
electromagnetic valve 18  
controller 19  
driver 20  
gap of magnetic suspending 21  
cylindrical air bearing surface 22  
air inlet 23  
magnetically suspended thrust bearing 24  
magnet block of bearing 24a  
coil of bearing 24b  
throttle hole in cylindrical air bearing surface 25  
air pipe 26

The invention claimed is:

1. A magnetically suspended vibration isolator with zero stiffness, comprising:

a upper mounting plate (1),  
a lower mounting plate (2),  
a main body (4) fitted between the upper mounting plate (1) and the lower mounting plate (2), and  
a clean air compressor (3) connected to the main body (4) through an air pipe (26);

wherein the main body (4) comprising

a downside-down sleeve (6) lubricated and supported against the lower mounting plate (2) by a magnetically suspended thrust bearing (24),

a upside-down piston cylinder (5) fitted in the sleeve (6) and lubricated against the sleeve (6) by a cylindrical air bearing surface (22),

a joint ball bearing (7) fitted between the piston cylinder (5) and the upper mounting plate (1);

a voice coil motor in a vertical or Z direction (10) for providing a vertical driving force, a displacement sensor in the Z direction (13) and a limit switch in the Z direction (16) having respective sensitive directions along the direction of the vertical driving force that are fitted between the piston cylinder (5) and the sleeve (6);

a voice coil motor in a first horizontal or X direction (8) for providing a first horizontal driving force, a displacement sensor in the X direction (11) and a limit switch in the X direction (14) having respective sensitive directions along the direction of the first horizontal driving force that are fitted between a sleeve cylinder (6) and the lower mounting plate (2);

a voice coil motor in a second horizontal or Y direction (9) for providing a second horizontal driving force perpendicular to the first horizontal driving force, a displacement sensor in the Y direction (12) and a limit switch in the Y direction (15) having respective sensitive directions along the direction of the second horizontal driving force that are fitted between the sleeve cylinder (6) and the lower mounting plate (2);

a controller (19) having signal input terminals connected to the displacement sensor in the X direction (11), the displacement sensor in the Y direction (12) and the displacement sensor in the Z direction (13) as well as the limit switch in the X direction (14), the limit switch in the Y direction (15) and the limit switch in the Z direction (16) and signal output terminals;

9

a driver (20) having signal input terminals connected to signal output terminals of the controller (19) and signal output terminals connected to the voice coil motor in the X direction (8), the voice coil motor in the Y direction (9) and the voice coil motor in the Z direction (10) respectively,

wherein an air pressure sensor (17) is fitted inside the piston cylinder (5) which is connected to a signal input terminal of the controller (19), a signal output terminal of the controller (19) is connected to a signal input terminal of the driver (20), and a signal output terminal of the driver (20) is connected to the electromagnetic valve (18) fitted in the piston cylinder (5), and

wherein the magnetically suspended thrust bearing (24) is configured as follows: a magnet block of bearing (24a) is fitted on the bottom of the sleeve (6), a coil of bearing (24b) is oppositely fitted on the top of the lower

10

mounting plate (2), and the thickness of the gap of magnetic suspending (21) is 0.01 mm~1 mm.

2. A magnetically suspended vibration isolator with zero stiffness according to claim 1, wherein the voice coil motor in the X direction (8), the voice coil motor in the Y direction (9) and the voice coil motor in the Z direction (10) are cylindrical voice coil motors or flat voice coil motors.

3. A magnetically suspended vibration isolator with zero stiffness according to claim 1, wherein the limit switch in the X direction (14), the limit switch in the Y direction (15) and the limit switch in the Z direction (16) are mechanical limit switches, Hall limit switches or photoelectric limit switches.

4. A magnetically suspended vibration isolator with zero stiffness according to claim 1, wherein the air pressure inside the piston cylinder (5) is within a range of 0.1 MPa~0.8 MPa.

\* \* \* \* \*